

Precision Crystal Frequency Reference Disciplined Using Mains Power

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Abstract—We describe a clock that keeps time and provides a reference frequency with better than 1PPM accuracy, through a quartz crystal automatically calibrated via the power line frequency. The long-term precision of line-frequency-based time is used to correct the crystal-based timekeeping system, a process referred to as disciplining. A microcontroller calibrates the internal reference dynamically with no user assistance. Precision is improved to better than 1ppm as measured against a rubidium standard. The precise signal is useful for calibrating frequency-based instrumentation or keeping time without periodic correction and costs much less than comparable alternatives. The algorithm can be implemented in any mains-powered device using a microcontroller, such as thermostats and lighting timers. The prototype clock uses a Nixie-tube display, requires no transformer, is housed a glass tube, and is offered as an open-source design.

Index Terms—Clocks, frequency measurement, counting circuits, power system measurements, crystal disciplining

I. INTRODUCTION

The properties of quartz crystals were a hot topic in the 1920s, and by 1930 the quartz crystal emerged as a technology to realise frequency-stable oscillators [1]. The second world war saw their application to radio and microwave systems, and by the 1950s quartz crystals were found at the heart of national frequency standards [2]. As the size, cost and power consumption of quartz crystal systems improved through the 20th century, domestic clocks moved from using synchronous motors locked to line frequency to keep time to using internal quartz-crystal (“xtal”) circuits, and wristwatches moved from escapements to low-frequency crystal oscillators. In 1950, virtually all wall clocks used mains power. In 2000, most wall clocks used crystals. The annoyance of a power cord and power cuts was traded for the annoyance of changing batteries every year or so.

Clocks in the 21st century typically use one of three sources to keep time: the line frequency, an internal quartz-crystal, or a remote source such as the internet, cellular-phone system, or positioning satellites. The latter remote alternative has the advantage that the time is collected from the remote site and thus the clock never needs to be set, but the disadvantage of depending upon access to an external signal, and usually a need for rechargeable batteries. As of the second decade of this century the crystal is the dominant alternative, although increasing numbers of people, especially teenagers, eschew watches as they carry smart phones. All of these offer better timekeeping than most users need, but ironically the crystal is horologically the weakest, as it needs individual calibration in manufacture.

Quartz crystals are manufactured with something like 100ppm accuracy, or 20ppm accuracy if used with exactly

the prescribed loading capacitance. This corresponds to one or more minutes/month or 10 minutes to an hour per year. Wrist-watches achieve about 1ppm accuracy with factory calibration, typically via firmware or pulse-based correction circuits, and with careful design expect to achieve 2–5ppm over the life of the product [3]. Oven-controlled quartz-crystal standards are today available with 1ppm precision, but these tend to be quite expensive and power hungry, more than the low-cost instruments with which you might use them.

This manuscript describes a simple, low-cost scheme to “discipline” a quartz-crystal oscillator to automatically calibrate it to better than 1ppm accuracy using the mains power line frequency as the higher-precision reference. The attraction of this approach is that it comes at virtually no extra cost to any system that uses mains power, has a crystal for timekeeping and that is controlled with a microprocessor, as do many building systems and appliances. It would be equally possible to use an external, radio-based, time reference, if that is already available, but these are less common. The idea of using an external time reference to gradually refine a dynamic calibration for a crystal oscillator is not new [4]. Nevertheless, this particular work employs that principle to simultaneously produce an elegant timepiece and a laboratory-grade frequency reference in a very low-cost, robust, open-source, and rather elegant, design.

II. PRECISION

Line power cumulative frequency time error is tightly controlled in New Zealand, with the Electricity Commission “ensuring the cumulative frequency time error does not exceed 5 seconds and that the error is eliminated at least once per day” [6]. The precision with which a frequency can be determined, and a calibration factor calculated, increases with the length of the observation. Five seconds is one-millionth part of 58 days, so the cumulative-frequency error of a mains power observation will approach 1ppm only after a two-month observation. Mathematically

$$M = T + \delta \quad (1)$$

where M is time according to the mains frequency, T is the true time, and δ is the maximum error, 5 seconds in our case, while

$$X = T \times (1 + \epsilon) \quad (2)$$

where X is time according to the crystal to be calibrated, and ϵ is the error to be determined and corrected. We seek an estimate of ϵ given bounds on δ . Some algebra leads to

$$\epsilon = \frac{X - M + \delta}{T} \approx \frac{X - M}{M} \quad (3)$$

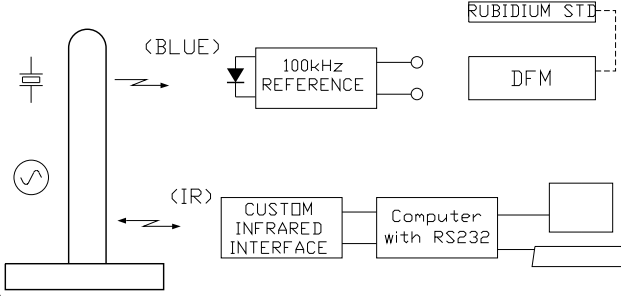


Fig. 1. Block diagram of the system as implemented. The rubidium standard is used to verify performance and is eventually replaced by the device itself.

if δ is small, M large, and temperature variations are negligible. This provides a simple path to obtain an estimate of ϵ . Knowing that $|\delta| < 5s$, the uncertainty in an estimate is δ/M , corresponding to about 1ppm when $M = 5 \times 10^6$ or the 58 days noted above.

We know also that $M = T$ at least once per day. It may thus be possible to reduce the uncertainty. If the diurnal variation, δ_{max} is less than 5 seconds, then $\delta \leq \delta_{max}$ in that period since it must have been zero somewhere in the day, and the uncertainty is reduced. It was observed from clock performance that the convergence rate is greater than expected from theory.

III. HARDWARE

Figure 1 depicts the system arrangement. The basic unit incorporates a crystal and mains-power monitoring in a free-standing device that functions as a clock. Control of the clock is provided through a custom infrared (IR) serial data interface to a Raspberry Pi computer, although it can function perfectly well without this interface. A reference signal is provided for the calibration of instrumentation. For our work here a rubidium standard frequency generator is interfaced with a digital synthesizer to verify performance, but a Digital Frequency Meter (DFM) will also work provided it has sufficient digits of resolution.

The clock hardware requires a microcontroller with both a crystal oscillator and access to line power frequency. We have chosen to use a PIC16F1709 because it offers an in-built, current-based, zero-crossing detector peripheral, serial communications support, plenty of memory, crystal oscillator, temperature measurement, non-volatile storage, and all the usual features of modern 8-bit microcontrollers. It retails locally for around \$2 in small quantities. Power consumption is around $350\mu A$ when clocking at 1 Mips and with all peripherals shut down to conserve power. We have based our design on a very elegant clock designed by Dekker and de Graaf [5]. Their clock operates directly on the mains voltage, requiring no transformer, and displays time using a single Nixie-style neon display tube. For safety and novelty the

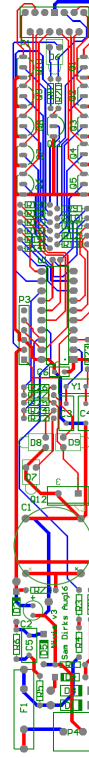


Fig. 2. The PCB layout of the hardware

original is mounted inside a one-inch-diameter (25mm) glass test-tube.

For our design, a supercapacitor to allow operation without mains power for approximately 2.5 hours, and optical interfaces for exchange of data and for the delivery of the frequency standard signal. The circuit diagram is reproduced in figure 3 with the PCB layout in figure 2. We also house the device in a glass tube extended to 300mm height and 30mm outside diameter.

IV. FIRMWARE

The PIC16F1709 carries out the following functions:

- Count mains cycles since the first zero crossing of a contiguous sequence
- Count processor clock cycles since the first zero crossing of a contiguous sequence
- Detect missed mains cycles/loss of mains power
- Compute correction factors for crystal from cycle counts
- Calculate current time given clock cycles, correction factor, and uncertainty
- Display time and key data on display tube sequentially by fading digits in and out
- Receive commands and supply data via IR serial link
- Generate reference frequency in blue light

Correction of the crystal clock frequency occurs in increments of approximately 1 part in 60 million, or 0.017ppm. This is achieved in the firmware by dynamically adjusting the number of nominal-1 μs computer clock cycles in each minute. To

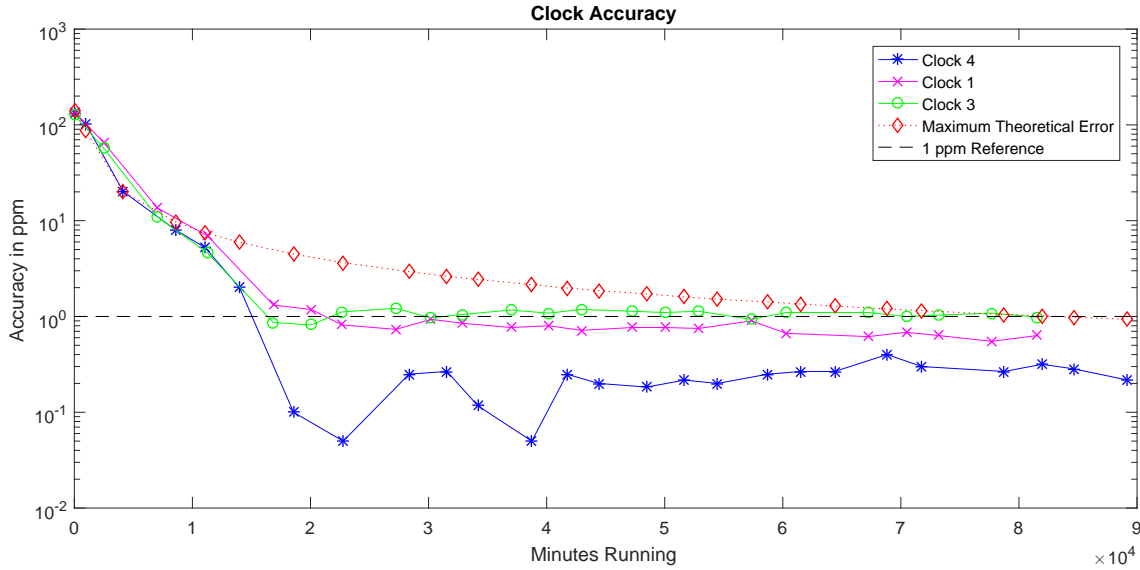


Fig. 5. The accuracy of the clocks with respect to the time running in minutes. For reference the maximum theoretical error and 1 ppm lines are included.

VI. MEASURED RESULTS

The accuracy calculation was made by comparing the crystal frequency calculated from LED frequency measured and the crystal frequency as calculated by the clock. The frequency of the LED for the clocks were 100.013 653 kHz, 100.012 747 kHz and 100.012 351 kHz respectively for clocks 1, 3 and 4 respectively.

Figure 5 shows the accuracy of the clocks with respect to time. This clearly illustrates the clock 4 achieving an accuracy of 1 ppm after only 16,000 minutes and reaching an equilibrium of approximately 0.3 ppm. Clocks 1 and 3 reached approximately 1 ppm in 17,000 minutes. However they did not reach the same level of accuracy as clock 4.

Clock 4 was run on an open air bench in the laboratory against an internal wall with the only building ventilation controlling room temperature. Clocks 1 and 3 were placed in a windowsill in another room and received direct sunlight for part of the day. As they both had a higher noise floor of similar magnitude we conclude that environmental factors are the limiting case.

The time taken to achieve 1 ppm for clock 4 of 16,000 minutes or 11 days also shows that the regulation of mains frequency is much better than the minimum requirements which would require 58 days.

VII. CONCLUSION

The precision mandated for power-line frequency has been used to provide a very accurate frequency reference through firmware discipline of a crystal oscillator. This is achieved on a very low-cost platform.

A GPS or GSM time fix could provide a 5x reduction in the time required to achieve maximum accuracy in exchange for access to an RF signal, more circuitry, and cost. Nevertheless, the design presented here can provide a laboratory-grade

signal of well-known frequency, or a low-frequency signal of precisely-known period. Automatic correction for ageing and environment could be included in a future development. The devices look attractive and tell the time without either primary or rechargeable batteries or resetting of the time with modest-duration power outages.

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REFERENCES

- [1] Lucas, H.J., "Some developments of the piezo-electric crystal as a frequency standard", *Journal of the Institution of Electrical Engineers*, Vol. 68, no. 403, 1930, pp855–867.
- [2] Shaull, J.M., and J.H. Shoaf, "Precision Quartz Resonator Frequency Standards" *Proceedings of the IRE*, Vol 42, no. 8, 1954, pp1300–1306.
- [3] Lanfranchi, D., E. Dijkstra, and D. Aebischer, "Microprocessor-based analog wristwatch chip with 3 seconds/year accuracy", *Digest of Technical Papers of the 41st ISSCC, IEEE International Solid-State Circuits Conference*, 1994, pp92–93.
- [4] Helsby, N.C., "GPS disciplined offset-frequency quartz oscillator", *Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition Jointly with the 17th European Frequency and Time Forum*, pp435–439, 2003.
- [5] Ronald Dekker, and Pascal de Graaf, "Tube-in-a-Tube Clock", see <http://www.dos4ever.com/TiT/TiT.html>, retrieved December 2014.
- [6] Electricity Commission of New Zealand, "Current Arrangements for Frequency, Voltage, Reliability and Security", Chapter 3, 461406-2, accessed December 2014.